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WATERPROOFING STRAIN GAGES FOR LOW AMBIENT TEMPERATURES

Donald E. Garfield and Bryan G. McLain

September 1978

COLD REGIONS RESEARCH AND ENGINEERING LABORATORY
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Due to recent problems experienced with strain-gage based transducers immersed in water at below-freezing ambient temperatures, a test program was conducted to determine if commercially available strain-gage waterproofing systems could withstand these conditions. A total of 96 combinations of eight waterproofing systems, three beam materials, and four strain gage adhesives were evaluated. Test environments included strain cycling at temperatures from +32°F to +75°F and freeze-thaw cycling from -35° to +90°F. Only one waterproofing system withstood all tests with no failures. Other results ranged from one installation failure on three systems to the failure of all 12 installations of one system.

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PREFACE

This report was prepared by Donald E. Garfield, Research Mechanical Engineer, of the Engineering and Measurement Services Branch, Technical Services Division and Bryan G. McLain, Engineering Aide, Applied Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided under DA Project 4A161101A91D *In-House Laboratory Independent Research*, Budget Subactivity 611101, *Strain Gage Transducers Operating in Extreme Environments*.

The authors gratefully acknowledge the advice and assistance provided by John Kalafut and the technical review of the report by Herbert Ueda and Dr. Donald Nevel of CRREL.

The contents of this report are not to be used for advertising or promotional purposes. Citation of brand names does not constitute an official endorsement or approval of the use of such commercial products. Although test results indicated that certain commercial products were superior under the imposed conditions, similar products manufactured by other companies may perform equally well.

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CONVERSION FACTORS: U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

These conversion factors include all the significant digits given in the conversion tables in the ASTM *Metric Practice Guide* (E 380), which has been approved for use by the Department of Defense. Converted values should be rounded to have the same precision as the original (see E 380).

Multiply	*By*	*To obtain*
inch	25.4*	millimeter
microinch	0.0254*	micrometer
pound-force	1.355818	newton
pound-force/inch^2	6.894757	kilopascal
degrees Fahrenheit	$t_{°C} = (t_{°F} - 32)/1.8$	degrees Celsius

* Exact

WATERPROOFING STRAIN GAGES FOR LOW AMBIENT TEMPERATURES

Donald E. Garfield and Bryan G. McLain

INTRODUCTION

Strain-gage based transducers have been successfully used in cold environments for a number of years. Recently, however, CRREL has experienced a number of failures when load cells, which were supposedly waterproofed, were subjected to repeated immersion in water with ambient temperatures below freezing. In one case a load cell that had been used in the field was found to be faulty when it was calibrated just prior to the following field test season. Since this load cell was stored in a coldroom which was temperature cycled over the summer months, and the load cell was not calibrated immediately after the previous test season, it is uncertain whether damage occurred during the winter testing period or during the summer storage period. Thus data obtained during one entire season are subject to question.

This experience has pointed up the need to find a strain gage waterproofing system which can withstand low ambient temperatures and repeated water immersion. Published literature reveals many efforts to discover a waterproofing system which would withstand long-term water immersion. Most of these investigations occurred in the 1950's. Dean (1957) reported on a successful combination of wax, rubber, and stainless steel shim stock, which was the forerunner of a commercially available waterproofing system, M-Coat F, from Micro-Measurements. Other investigators (e.g. Newton et al. 1959 and Wells 1958) used combinations of waxes, greases, foils, rubber, or epoxy. None of the reported tests included water immersion with freezing ambient temperatures. This indicated that a test program should be initiated to evaluate the effects of low ambient temperatures and water immersion on various strain gage waterproofing systems.

Laboratory tests, which duplicated field conditions as closely as possible, were designed to evaluate waterproofing systems. Cantilever beam specimens of commonly used steel, aluminum, and stainless steel were instrumented with strain gages. The strain gages were covered with different waterproofing systems selected from commercial sources. A test apparatus was constructed to allow testing several specimens simultaneously. Tests were performed by subjecting the cantilever beam specimens to various temperature environments and water immersion, in addition to strain cycling when environmental conditions permitted. After tests were completed in each environment, electrical measurements of gage integrity were made to determine if the waterproofing remained intact.

PROBLEM DEFINITION

In order to design the laboratory tests several questions needed to be answered:

1. **What types of field environments cause strain-gaged load cell failures?**
2. **What are some possible means by which water can get into the strain gage assembly?**
3. **How is strain gage performance affected by the water?**
4. **What non-destructive tests can be performed to determine the presence of moisture?**

These questions will be answered in the following paragraphs.

At least two possibilities exist to explain how water intrudes into a strain-gaged area and damages load cells. One explanation is the presence of pin holes in the lead wire insulation, which allow water to leak either inside the load cell housing or directly to the lead wire solder tab. A second possible explanation is that water leaks inside the load cell housing through the seals in the

housing itself. By exposing the initially warm transducer to low ambient temperatures, and then immersing the transducer in relatively warm water, it is conceivable that differential thermal expansion in the load cell components creates a large enough gap for water to enter. It is not known whether the gages fail abruptly, or whether failure occurs over a period of time; however, the latter is suspected.

Strain gages are affected by direct contact with water or by atmospheric water vapor. Both the gage carrier and the adhesive absorb water, which can affect gage performance in several ways. First, the moisture decreases the gage-to-ground resistance, effectively placing a shunt resistor across the gage terminals. Secondly, the water decreases the strength and rigidity of the adhesive bond, which reduces the strain transmission from the specimen to the gage filament. Thirdly, since plastics expand when moisture is absorbed, indicated strains may be produced which are not the result of mechanical strain in the specimen. Finally, the water present in the gage adhesive will cause electrolysis due to current leakage, eroding the gage filament which significantly changes gage resistance.

It should be pointed out that electrical current leakage can occur at any point in the circuit, including the lead wires or connectors, as well as in the gage itself. These leakage currents will also produce the first effect described above. Lead wire leaks may also cause "wicking" of the water into the gage assembly itself, producing all four effects described above.

Tests for the presence of moisture can be made by measuring zero shift in the gage circuit or by measuring electrical resistance between the gage and ground (specimen). The former test is not as specific as the latter, since a zero shift could also be caused by poor adhesive bonding, gage creep, or yielding in the instrumented specimen. The latter test should be performed using a low voltage tester, since an insulation breakdown at high voltage could destroy a good gage.

The following analysis shows that the effects on gage integrity due to a change in gage-to-ground resistance can be predicted using basic electric circuit concepts (Palermo 1956). Consider that only one gage (R_1) in a Wheatstone bridge has a finite measurable resistance to ground. This appears as a shunt resistance change across the gage terminals (Fig. 1).

Figure 1. Circuit for shunt resistance across gage terminals.

The equivalent resistance from A and B with an initial shunt in the circuit is

$$R_{e_1} = \frac{R_1 R_G}{R_1 + R_G} \quad (1)$$

where R_1 = gage resistance (ohms)
R_G = initial resistance to ground (ohms)
R_{e_1} = initial equivalent resistance (ohms).

If R_G decreases by an amount δ, the equivalent resistance from A to B is

$$R_{e_2} = \frac{R_1(R_G - \delta)}{R_1 + R_G - \delta}. \quad (2)$$

The effective change in circuit resistance ΔR_1 is given by

$$\Delta R_1 = R_{e_2} - R_{e_1}$$
$$= \frac{R_1(R_G - \delta)}{R_1 + R_G - \delta} - \frac{R_1 R_G}{R_1 + R_G}$$
$$= -\frac{R_1^2 \delta}{(R_1 + R_G)(R_1 + R_G - \delta)} \quad (3)$$

Assuming that R_1 is much lower than R_G, we obtain the following relationship:

$$\frac{\Delta R_1}{R_1} \approx -\frac{R_1 \delta}{R_G(R_G - \delta)}. \quad (4)$$

But $\Delta R_1 / R_1 = K\epsilon_1$, where ϵ_1 is the equivalent strain and K is the gage factor for the strain gages. Rearranging terms we then obtain

$$K\epsilon_1 = -\left(\frac{\delta}{R_G}\right)\left[\frac{R_1}{\left(1 - \frac{\delta}{R_G}\right)}\right]\frac{1}{R_G}$$

or

$$\epsilon_1 = -\frac{1}{KR_G} \cdot \frac{\delta}{R_G}\left[\frac{R_1}{\left(1 - \frac{\delta}{R_G}\right)}\right]. \quad (5)$$

In a Wheatstone bridge circuit shown in Figure 2, the governing equation (Murray and Stein 1963) is

$$\frac{e_{out}}{V_{in}} = \frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) \quad (6)$$

where V_{in} is the input voltage to the bridge, and e_{out} the output voltage from the bridge.

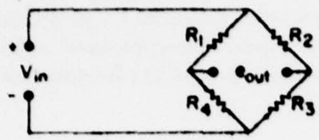


Figure 2. Gages in Wheatstone bridge.

In terms of equivalent strains we have

$$\frac{1}{4}\left(\frac{\Delta R_1}{R_1} - \frac{\Delta R_2}{R_2} + \frac{\Delta R_3}{R_3} - \frac{\Delta R_4}{R_4}\right) =$$

$$= \frac{K}{4}\left(\epsilon_1 - \epsilon_2 + \epsilon_3 - \epsilon_4\right) . \qquad (7)$$

Note from this equation that, if initial conditions (i.e. gage resistance and gage-to-ground resistance) were the same for gages 1 and 2 and both gages decreased by the same amount in their gage-to-ground resistance, these changes would offset each other and no zero shift would occur. However, since resistances R_1 and R_2 have effectively been shunted, a change in sensitivity and hence calibration would occur. Thus some caution must be used in interpreting the cause of a zero shift in a bridge circuit.

Assuming an initial gage-to-ground resistance of 20,000 MΩ in a full bridge circuit, we can calculate the zero offset that would result if the resistance to ground in one gage decreased, for example, to 100 MΩ. Since the gage factor for our gages was 2.05 and initial gage resistance was 350 ohms, the resulting equation is

$$\frac{\delta}{R_G} = \frac{(20{,}000 - 100) \times 10^6}{20{,}000 \times 10^6} = 0.995$$

and from eq 5:

$$\epsilon = -\frac{1}{2.05 \times 20{,}000 \times 10^6}(0.995)\left[\frac{350}{(1-0.995)}\right]$$

$$\epsilon = -1.7 \times 10^{-6}$$

or -1.7 μin./in.

This is the equivalent strain output from a full bridge circuit due to the change in gage-to-ground resistance indicated above.

Since this is about the limit of readability of our strain indicator and exceeds even the 0.1% accuracy required of precision transducers (assuming 2000 μin./in. full scale indicated strain), the 100 MΩ limit was selected as the failure point in our gage-to-ground resistance measurements.

TEST MATERIALS AND EQUIPMENT

The materials selected for testing were all commercially available and, except for the waterproofing systems, were generally used in our laboratory.

Beam materials

Cantilever beams were chosen as the test specimens since four individual gages could be installed on them and could be wired into a Wheatstone bridge circuit to monitor possible zero shifts. The beam materials selected were those commonly used in our laboratory as transducer elements and structural elements. Three materials were selected: M1020 low carbon merchant quality steel, 6061-T6 aluminum, and 17-4 PH stainless steel. Beam cross-sectional dimensions of 1.0-in. width and 0.25-in. thickness were selected to reduce possible stiffening effects from the waterproofing systems. The 17-4 PH stainless steel beams were hardened to condition H1025, which is accomplished by heating the annealed beams to 1025°F, then cooling in air. Typical handbook values for these materials are yield strengths of 35,000 lbf/in.^{2} for mild steel (Joseph T. Ryerson & Sons 1976) and aluminum (Aluminum Company of America 1958) and 145,000 lbf/in.^{2} for stainless steel (Armco Steel Corp. 1966). Young's moduli for these materials are 30×10^6 lbf/in.^{2} for mild steel, 10×10^6 lbf/in.^{2} for aluminum and 28.5×10^6 lbf/in.^{2} for stainless steel.

Strain gages

Micro-Measurements Series WK strain gages with integral printed circuit terminals were used for the tests. These foil gages are fully encapsulated in a glass fiber reinforced epoxy-phenolic resin. The "K" alloy foil (nickel-chromium alloy) was selected because of its high endurance limit over wide temperature ranges (Freynik and Dittbenner 1976), good stability, and the self-temperature compensation availability. Gages with thermal expansion coefficients of 6×10^{-6}/°F were used on the mild steel and stainless steel beams, and 13×10^{-6}/°F on the aluminum beams. Although self-temperature compensation is not always necessary in full bridge circuits because of the inherent electrical compensation, it is desirable if one gage in the circuit fails and an external bridge completion resistor is used. A gage length of 0.25 in. and gage resistance of 350 ohms were specified. The nominal gage factor was 2.1. All gages to be mounted on each beam material were specified to have the same lot number to further ensure that all gages would respond alike to environmental changes.

Adhesives

Four adhesives were selected which would be compatible with the epoxy-phenolic encapsulated gages and

provide for evaluation of various room and elevated curing temperatures on adhesive performance. BLH Electronics EPY-150, EPY-350, and PLD-700, as well as Micro-Measurements M-Bond 610, adhesives were selected.

EPY-150 is a two-part epoxy-base adhesive compatible with all strain gages and may be used at temperatures from −300°F to +150°F. It is recommended for long-term test applications. Its curing temperature is from +70°F to +150°F, with a curing time of from 1 to 72 hours, depending upon the temperature. This adhesive achieves full cure in 72 hours at 75°F, but is sufficiently stable for some applications after a 12-hour cure at 75°F or a one-hour cure at 150°F. Gage clamping pressures of 5 to 15 lbf/in.^{2} are required. Pot life is 30 to 60 minutes and shelf life is 6 months at 75°F.

EPY-350 is a very thick paste-like single-component epoxy with a heat-activated hardener, recommended for operating temperatures from cryogenic to +400°F. A uniformly thick layer of 0.008 to 0.012 in. is applied to the gage bonding surface. Clamping pressures of 5 to 15 lbf/in.^{2} are required. Full cure requires heating to 350°F for two hours. The epoxy has a 4-month shelf life.

PLD-700 is a single-component unfilled polyimide adhesive used at operating temperatures from cryogenic to over +750°F. Curing procedures for this epoxy are more complex than other epoxies; however, full cure is achieved in 2½ hours at 500°F. Clamping pressures required are 35 to 45 lbf/in.^{2} Shelf life of this adhesive is 4 months at 75°F or 12 months at 45°F.

M-Bond 610 is a two-component, solvent-thinned epoxy-phenolic adhesive used for high performance applications at temperatures from cryogenic to over +700°F. Clamping pressures of 30 to 40 lbf/in.^{2} are required. Cure is accomplished in 1½ hours at 340°F, and a post-cure of one to two hours at 50°F above the highest anticipated operating temperature is suggested. Pot life is 2 to 6 weeks at 75°F, and shelf life is up to 12 months at 75°F.

Waterproofing

Waterproofing systems were selected from commercially available stocks and chosen mainly on the basis of withstanding low temperature operation and long-term water immersion. Some of the coatings were very simple to apply, which is quite important in field applications. Other coatings required curing at elevated temperatures, or other complex application procedures, which somewhat restricted their utility. The following BLH Electronics protective coatings were selected for evaluation: Barrier A, Barrier C, Barrier D, Barrier E, Barrier WC, and Barrier WD. Micro-Measurements coatings M-Coat F and M-Coat GL were also selected. A general description of each coating and detailed application procedures are discussed in a later section.

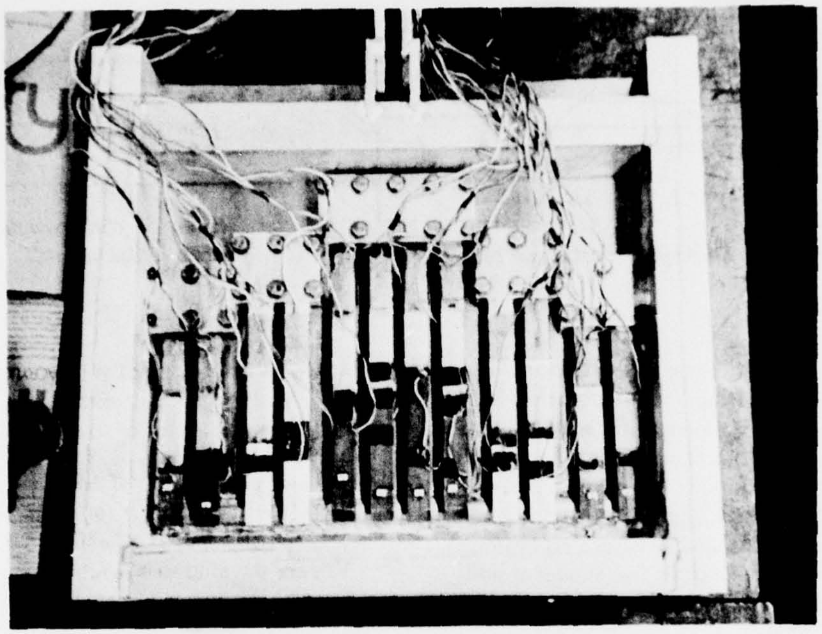
BEAM LOADING APPARATUS

The beam loading apparatus, shown in Figure 3, allowed testing of 12 cantilever beams (4 beams of each material) at one time. The beams were deflected with an automatically reciprocating air cylinder acting through a pivot arm. The Allenair Model AZ-VCR-4x3 cylinder with adjustable stroke kit KR-VCR-4 allowed adjustment in stroke frequency and beam deflection. The linkage was designed to provide approximately 1250 lbf on the beams with 100-lbf/in.^{2} air pressure, which exceeded the force required for the desired deflection of 12 beams (see App. A).

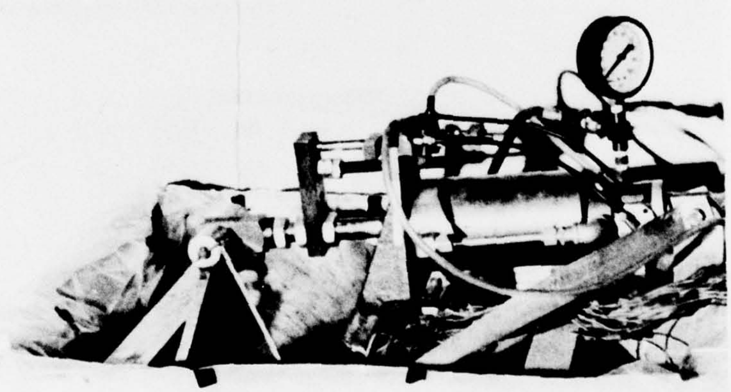
Cantilever beam specimens were used because a relatively simple loading mechanism could be built, and by placing four gages on each beam, four waterproofing systems could be evaluated with only one bridge circuit. Maximum beam deflections were arbitrarily limited to 0.375 in. It was desirable to obtain the maximum possible stresses in each material without exceeding the yield point. Since the size of the beams (0.25x1.0 in.) had already been selected and the maximum deflection set, the only variable left to achieve the desired stress level was beam length. From the analysis given in Appendix A, beam lengths selected were 11.25 in. for mild steel, 8.75 in. for aluminum, and 7.50 in. for 17-4 PH stainless steel.

The size of the strain gages and the requirement that the waterproofing material extend some distance (preferably at least ¼ in.) beyond the edges of the gage carrier dictated that gages could not be placed side-by-side across the 1-in. width of the beam. Instead, gages were placed as shown in Figure 4. Details of specimen preparation, gage mounting procedures, and lead wire testing are discussed in Appendices B, C, and D, respectively. The strain gages were all wired using identical lengths of vinyl-insulated lead wire. All gages were wired into a Wheatstone bridge circuit as shown in Figure 5. Strain measurements were taken in the bridge configuration, while gage-to-ground resistances were measured on each gage individually.

In order to predict the output from the Wheatstone bridge circuit with the gages placed as in Figure 5, one needs to calculate the strains at distances from the fixed end of 2.0 in. and 3.5 in., when the ends of the cantilever beams are deflected 0.275 in. The strains at the top surface of the beam are considered positive



a. Loading apparatus with test beams clamped in position.



b. Complete loading apparatus in operation.

Figure 3. Beam loading apparatus.

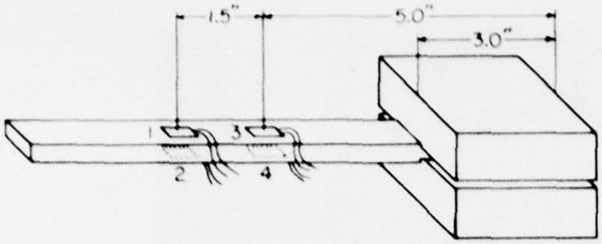


Figure 4. Strain gage location on beams.

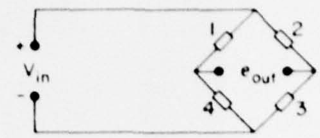


Figure 5. Wiring diagram for Wheatstone bridge circuit.

(i.e. in tension), while those on the bottom are negative (in compression). Strain magnitudes at positions 1 and 2 are equal, and strain magnitudes at positions 3 and 4 are also equal. From Appendix A, eq A1, the strain magnitudes at positions 1 and 2 are 7.654×10^{-4} in./in., 1.102×10^{-3} in./in., and 1.333×10^{-3} in./in. for the mild steel, aluminum, and stainless steel beams, respectively. Likewise the strain magnitudes at positions 3 and 4 are 9.136×10^{-4} in./in., 1.417×10^{-3} in./in., and 1.833×10^{-3} in./in. for the same respective beams.

The governing equation for strain gages in a Wheatstone bridge (Garfield 1975) is

$$\frac{e}{V} = \frac{1}{4}K(\epsilon_1-\epsilon_2+\epsilon_3-\epsilon_4) \qquad (8)$$

where e = bridge output voltage
V = bridge input voltage
K = gage factor of strain gages.

Using a gage factor of 2.05 for the series WK strain gages, bridge outputs at full beam deflections are 1.721×10^{-3} V/V, 2.582×10^{-3} V/V, and 3.245×10^{-3} V/V for the mild steel, aluminum, and stainless steel beams, respectively. These voltage ratios correspond to indicated strains of 3358 μin./in., 5038 μin./in., and 6332 μin./in. for the same respective beams.

TEST INSTRUMENTATION

A specific nondestructive test for the presence of water in a strain gage assembly is a measurement of insulation resistance between the gage and ground

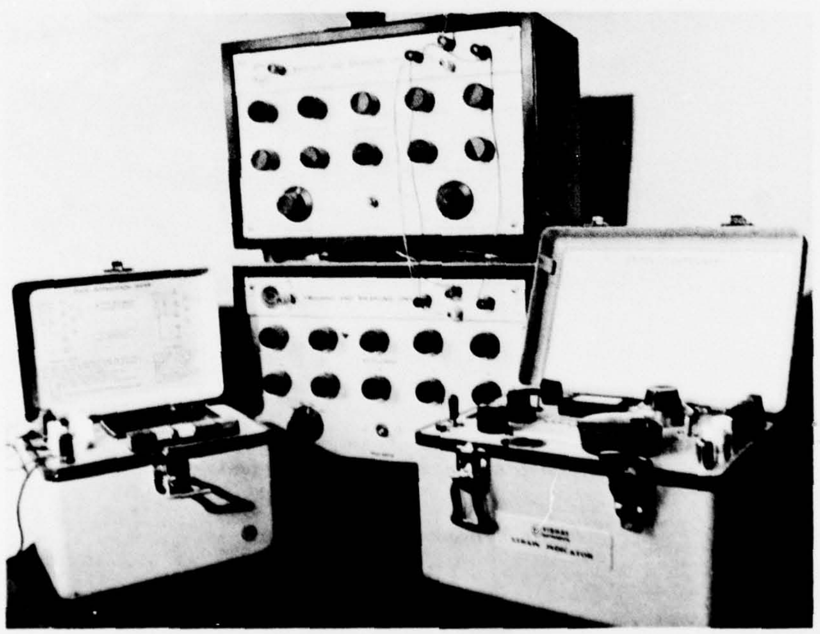


Figure 6. Test instrumentation.

(specimen). Any leakage path occurring between the strain gage or the lead wires to ground affects the accuracy of the strain measurements, and it was shown earlier that a resistance change from 20,000 MΩ to 100 MΩ in one gage results in a 1.7-μin./in. error. The Vishay Instruments Model 1300 gage installation tester was used for gage-to-ground measurements and also provided a means for accurately measuring gage resistance.

For the Wheatstone bridge hookups, two BLH Electronics type 525 switching and balancing units were used to initially balance each circuit before each test. A Vishay Instruments Model P-350A digital strain indicator was used to monitor the indicated strain in each bridge circuit (see Fig. 6).

WATERPROOFING INSTALLATION

In all cases, the beam specimens must be properly prepared for gage installation, the strain gages installed, the lead wires tested and soldered to the gages, and the complete installation again cleaned to remove all grease and oil before application of the waterproofing system. All these preliminary procedures were performed following the manufacturers' instructions, and are discussed in detail in Appendices B, C, and D. The following paragraphs provide detailed descriptions for applying each of the coatings. Figures 7 through 14 show completed installations of all waterproofing systems used.

Barrier A is a BLH Electronics product consisting of a fiberglass-Teflon pressure-sensitive silicone adhesive tape and a silicone sealer. Although the system appeared to be very simple to install, we experienced many problems with initial attempts at installation. The specimen surface was cleaned with methyl ethyl ketone (MEK). A piece of tape large enough to extend ¼ in. beyond the gage edges and ½ in. up the lead wires was cut and pressed firmly over the gage assembly. A heavy coating of silicone rubber was applied, overlapping the specimen and the tape about ¼ in. About ½ hour after the sealer was applied, the tape edges began to curl up. Several applications were attempted with only partial success. Finally the kit was returned to BLH Electronics, and their tests indicated a defect in the tape. A new kit was sent and no problems were experienced with this. More than one application of sealer was applied to the lead exit area, since the leads "wicked-up" some of the sealer. The sealer did not appear viscous enough to allow application of this system on vertical surfaces. The sealer cures in one hour at room temperature; however, it remains "tacky" indefinitely.

Barrier C, from BLH Electronics, is a single component, acid-free, translucent silicone rubber that is room temperature vulcanizing (RTV). Barrier C is also available from other distributors under other names and is simply a tube of Dow Corning 3140 RTV coating. This is also available in larger quantities to governmental agencies through GSA and is the same as Federal Stock Number 5970-791-3716 insulating compound. We modified the recommended application procedure by first applying a coating of Micro-Measurements M-Coat D. This was allowed to cure for two hours. Then a coating of Micro-Measurements M-Coat B was applied over the M-Coat D and extended up the gage leads to act as an insulation primer coat. After another two-hour cure the Barrier C was spread over the entire area. The RTV coating requires approximately 24 hours cure time for each 0.02-in. coating thickness at room temperature and 50% relative humidity.

Barrier D, available from BLH Electronics, is a two-part epoxy resin which comes in premeasured packages with a separator between the resin and the hardener. The epoxy is mixed by removing the separator and kneading the bag for about five minutes. The epoxy is applied with a spatula. A coating of less than ⅛-in. thickness is recommended to avoid reinforcing the specimen. For long-term water immersion, two coats of less than ⅛-in. thickness each are recommended. Because our specimens were only ¼ in. thick, we applied only one coating to avoid possible stiffening of the test beam. The coating was extended ¼ in. beyond three edges of the gages and ½ in. up the lead wires. The coating was cured for ½ to one hour under a heat lamp with specimen temperatures of 150° to 200°F.

Barrier E, another BLH Electronics product, is a soft Butyl rubber with a patch of unfabricated Neoprene rubber for mechanical protection. The patch was cut to size, allowing a ¼-in. border around the gage and ½ in. beyond the terminals at the lead end. The patch was then applied to the specimen and pressed firmly with the fingers. The Neoprene was pulled back slightly at the lead exit end and the Butyl rubber kneaded around and under the lead wires. Then the Neoprene jacket was replaced and pressed firmly to exclude all air bubbles. This was by far the easiest waterproofing coating to apply and required no curing.

Barrier WC, distributed by BLH Electronics, is a hard microcrystalline wax. The wax was heated to approximately 170°F to melt and then brushed on the specimen, which had been preheated to approximately 110°F. The wax was applied in layers to about ⅛ in. thick and finally smoothed over with a heated metal spatula. On the lead exit side of the gages the coating extended as far as practical, without interfering with

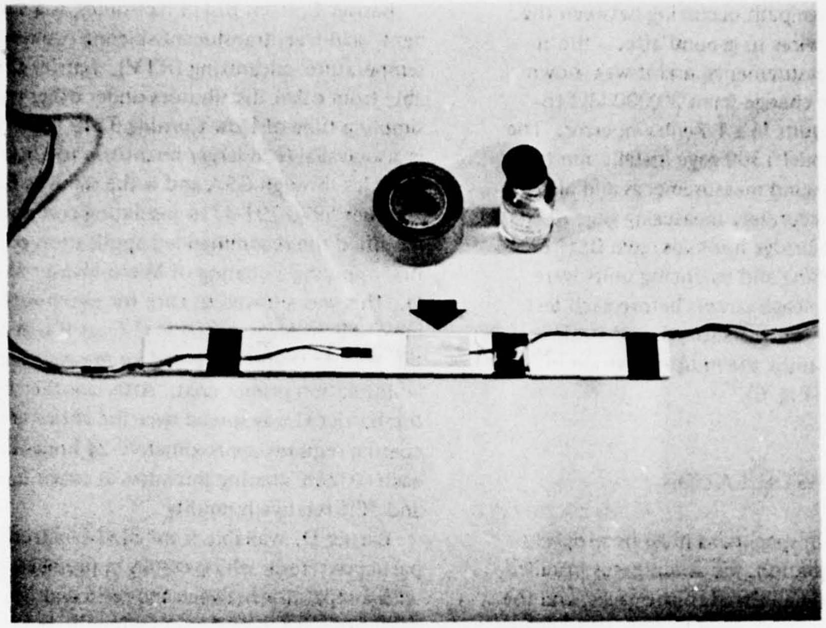


Figure 7. Barrier A installation.

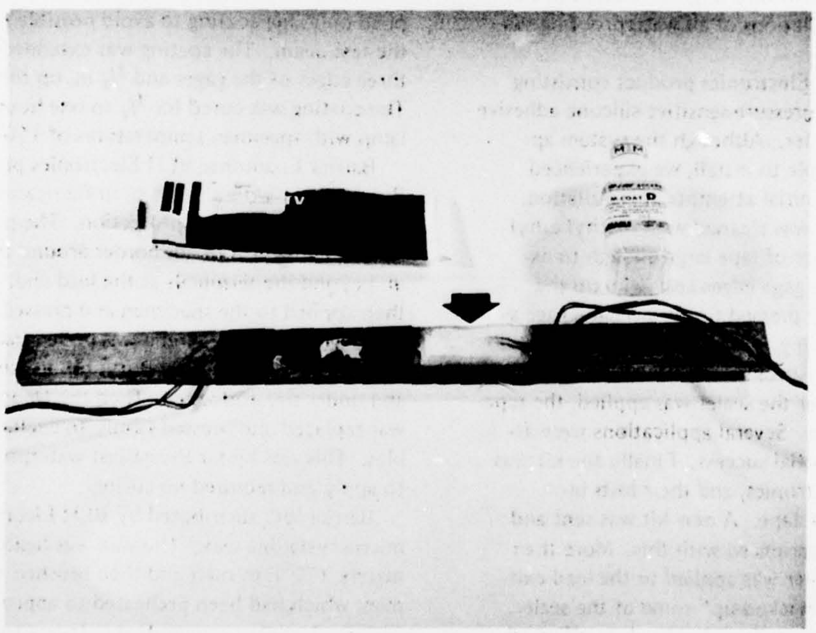


Figure 8. Barrier C installation.

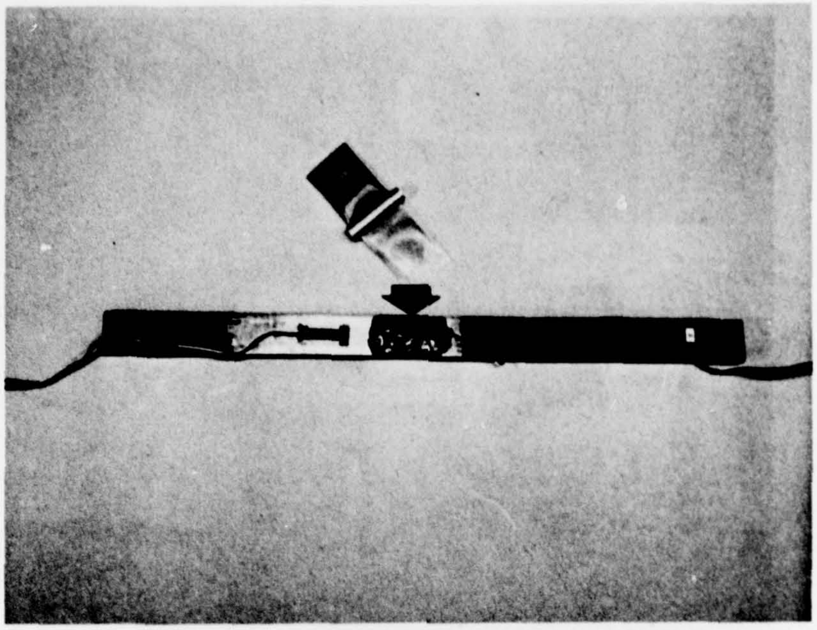


Figure 9. Barrier D installation.

Figure 10. Barrier E installation.

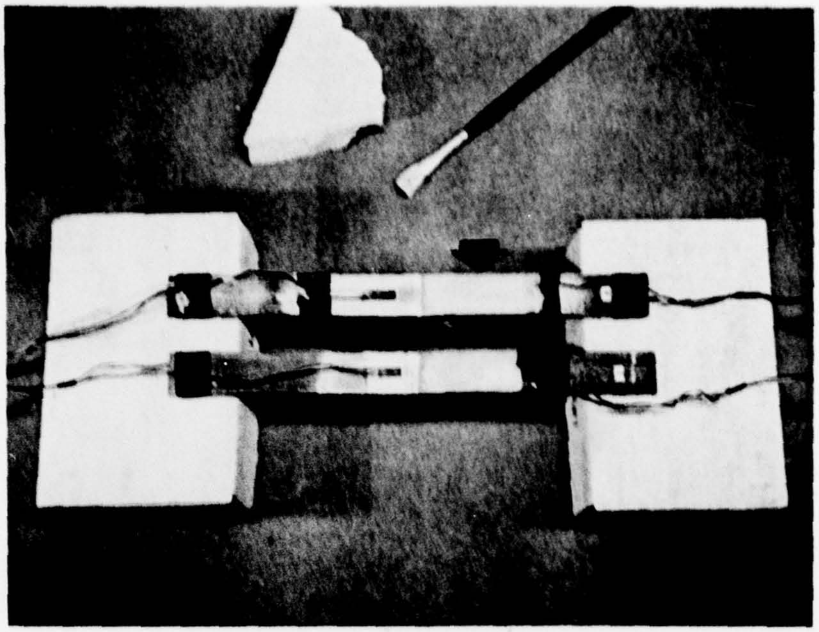


Figure 11. Barrier WC installation.

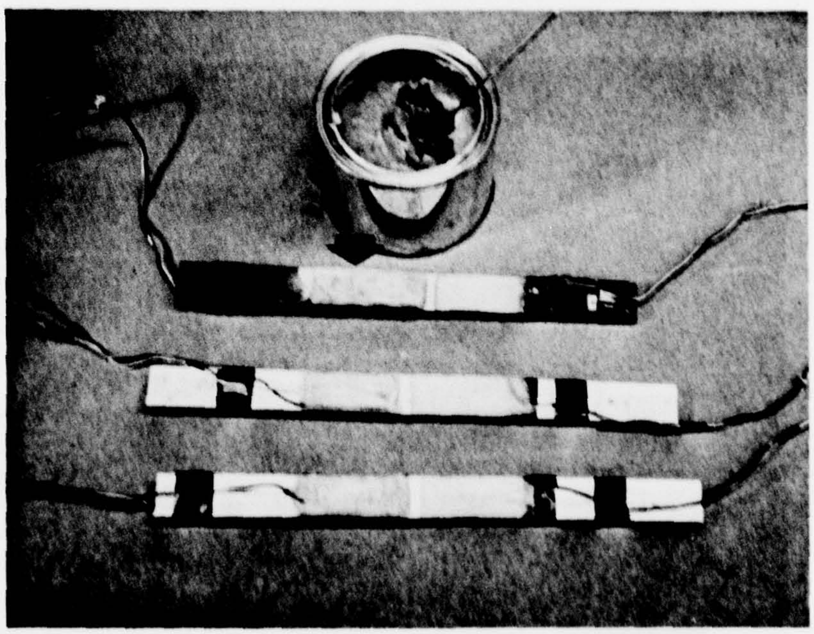


Figure 12. Barrier WD installation.

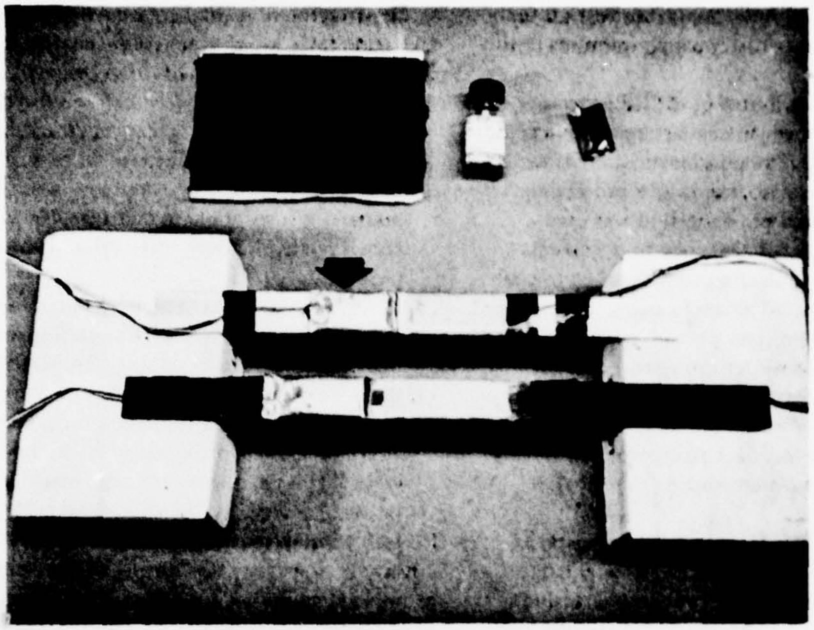


Figure 13. M-Coat F installation.

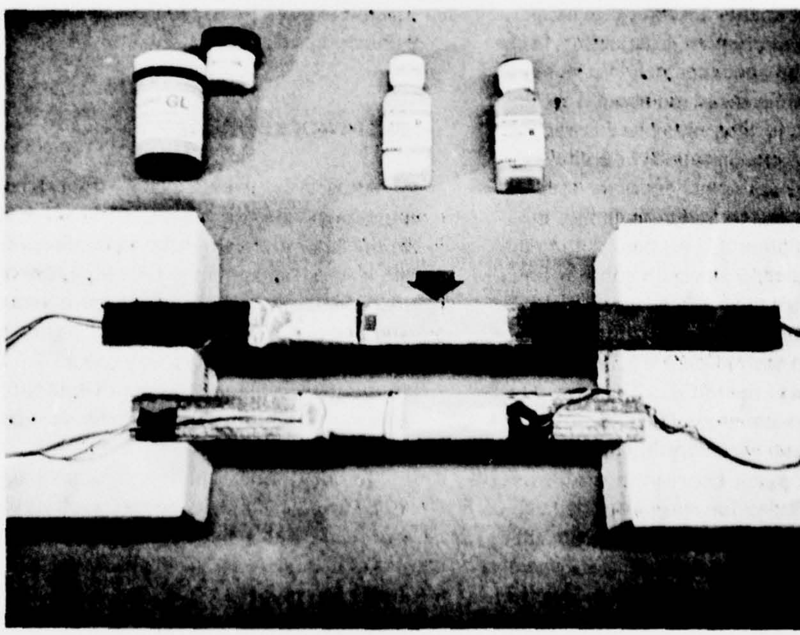


Figure 14. M-Coat GL installation.

the beam clamps, and ½ in. beyond the remaining gage edges. This coating cannot be applied to vertical surfaces; however, it is quite easy to apply to warm horizontal surfaces.

Barrier WD, also distributed by BLH Electronics, is a soft paste-like wax which can be applied to a cold surface with a spatula. The wax remains soft after application and provides no mechanical protection. The "buttering" method of application was used, since heating the wax has a tendency to degrade its adhesive characteristics. Extra care was taken to coat beneath the lead wires. After application, the lead wires were secured to prevent any movement which could form channels for water intrusion. Although the manufacturer recommends heating the specimen from 120° to 150°F if possible, we did not do this because the primary use for this coating would probably be in field installations where heating may not be possible.

M-Coat F, from Micro-Measurements, consists of an assortment of materials including a soft and pliable Butyl rubber sealant, Neoprene rubber sheets, aluminum foil tape, and M-Coat BT which is a solvent-thinned nitrile rubber. We used a sample kit of M-Coat F, which did not contain the aluminum tape; instead a Butyl rubber tape with a heavy aluminum foil backing (3M Scotch Tape No. SJ-8050X) was substituted. The lead wires were first coated near the gage area with M-Coat BT. When this primer dried, a Butyl rubber pad was cut to extend approximately ³/₈ in. beyond the three edges of the strain gages and about 1 in. up the lead wires. The Butyl rubber was placed over the gage area and carefully formed around the lead wires to eliminate possible leakage paths. Since we used aluminum foil tape over the complete assembly, the Neoprene patch was cut about ¹/₄ in. smaller than the Butyl rubber, which provided a smooth contour for the aluminum tape. After the Neoprene was placed in position, the aluminum tape was installed and the edges and corners sealed with M-Coat BT. We experienced some problems with the M-Coat F system. On the first installation attempt a heavy layer of M-Coat BT was applied to the lead wires with the idea that this would help fill in the gaps between the lead wires. The remainder of the installation was performed according to the manufacturer's instructions. When all completed installations were checked, the gages were essentially shorted to ground. Apparently the layer of M-Coat BT was too thick, preventing release of some of the solvent after cure was assumed to be complete. We assumed all applications of this system were a failure and removed them. On the second installation attempt, instead of allowing the M-Coat BT to dry for only two hours as recommended, we monitored the gage-to-ground resistance and when this value exceeded 10,000 MΩ, we considered the coating properly cured. We found curing times of up to three days at room temperature were required before subsequent layers could be applied. Particular care should be taken to prevent movement of the lead wires during the curing of M-Coat BT, since the vinyl insulation becomes very soft and is susceptible to damage. The vinyl again becomes relatively tough after this coating has cured properly.

M-Coat GL is distributed by Micro-Measurements and is a two-part, 100% solids, polysulfide modified epoxy in a pourable form. For long-term water immersion, the manufacturer recommends that a precoat of M-Coat D, which is a solvent-thinned acrylic, be brushed on an area extending approximately ¹/₄ in. beyond the gage edges. This coating is very thin, precluding application on vertical surfaces. Before applying M-Coat GL, the lead wires were coated with M-Coat BT and cured properly as previously described. The M-Coat GL was mixed and poured over the gage assembly, and it was smoothed with a glass rod, taking care to avoid trapping air bubbles in the coating. The vinyl wire insulation caused some "wicking" of the coating, which required a recoat in the lead wire area. This coating should be applied in a well-ventilated area. Cure was complete in 24 hours, and the coating acquired a tough, rubbery consistency.

TEST PROCEDURE

An ideal test would exactly duplicate all anticipated operating conditions; however, this is often impossible in the laboratory. In order to duplicate field conditions as closely as possible the following tests were proposed: load cycling the test beams at room temperature in air and under water, and the further testing of the beams in air at 32°F and under water at 32°F. In addition, freeze-thaw cycle tests were run without load cycling (since it was impossible to flex the ice-shrouded beams) at temperatures from -35° to +90°F.

The first part of the test program involved testing 12 beams, which included four each of the mild steel, aluminum, and stainless steel specimens. The first set tested included each of the four gage adhesives (EPY-150, EPY-350, PLD-700 and M-610) and four waterproofing systems: Barrier WC, Barrier WD, M-Coat GL, and M-Coat F. Initial measurements were taken of gage-to-ground resistance, gage resistance, and indicated strains with the beams undeflected and fully deflected. The beams were then load cycled 100,000 times in

each of the environments described above. After each test, measurements were again taken on each gage and each bridge to determine if failures had occurred and possible causes of the failures. The bridge circuits were then rezeroed before load cycling in a new environment.

The second set of 12 beams tested also included the same beam materials and adhesives as the previous set; however the waterproofing systems were Barrier A, Barrier C, Barrier D, and Barrier E. The beams were subjected to the same environments and load cycles as before, and identical measurements were taken to determine the gage assembly integrity.

The test apparatus was constructed to load the beams in only one direction, and so two gages on each beam were loaded in tension for each set of tests, and the other two were loaded in compression. It was originally intended to turn the beams over after the completion of one test series so that each gage assembly would experience both tensile and compressive strains. One set of beams was load cycled in air at 70°F and 32°F and in water at 32°F, then turned over and the tests repeated. No additional failures were recorded after the beams were turned over. The other set of 12 beams was tested under identical conditions and the beams turned over as before. The loading apparatus failed before completion of the last test series. We decided not to repair the loading apparatus and complete this test series since, as stated before, no additional failures had occurred in the other set of beams after turning them over.

Both sets of beams were then placed in containers of water and put through a more rigorous freeze-thaw cycle without loading the beams. Initial readings were taken at room temperature in air and in water. Four freeze-thaw cycles were performed at temperatures of +22°F and +75°F respectively and six more cycles performed at freeze-thaw temperatures of -30° and +75°F respectively. The gages were tested for leakage following each individual cycle and then finally monitored for two days while drying in air at +75°F. This gave an indication of which assemblies contained trapped moisture that could not be easily dried. The fact that the direction of load cycling was not reversed on the one set of beams was of no concern since the majority of failures occurred during the more rigorous freeze-thaw cycles.

At the completion of all assembly testing, the lead wires were removed from all gage assemblies that were determined to be faulty. Resistance-to-ground measurements were again performed on the wires only to determine if leakage occurred through the lead wire insulation.

TEST RESULTS

The test results are summarized in Tables I through III. Table I shows that Barrier D was the only waterproofing system that passed all tests without any failures. As noted earlier, only one coat of this epoxy was applied instead of the two coats recommended. Three systems, M-Coat GL, M-Coat F, and Barrier E, each had one failure out of 12 installations; while Barrier A only had two failures out of 12 installations.

Failures of the M-Coat GL, M-Coat F, and Barrier E systems occurred at the very start of the tests, indicating that these installations may have been initially faulty.

Tables II and III show the correlation between adhesive type or specimen material and waterproofing failure. Although more failures occurred on mild steel

Table I. Gage assembly failures related to waterproofing type.

Waterproofing	*Total assemblies*	*Failures*	*Failures (%)*
Barrier WC	12	12	100
M-Coat GL	12	1	8
Barrier WD	12	6	50
M-Coat F	12	1	8
Barrier D	12	0	0
Barrier A	12	2	17
Barrier E	12	1	8
Barrier C	12	3	25

Table II. Gage assembly failures related to specimen material.

Material	*Total assemblies*	*Failures*	*Failures (%)*
Mild steel	32	11	34
Stainless steel	32	9	28
Aluminum	32	7	22

Table III. Gage assembly failures related to adhesive.

Adhesive	*Total assemblies*	*Failures*	*Failures (%)*
EPY-150	24	8	23
EPY-350	24	6	25
PLD-700	24	6	25
M-Bond 610	24	6	25

specimens than on the other two, it is difficult to draw any conclusions about the possible cause of this. Also, more failures occurred on the strain gages cemented with EPY-150 adhesive; however, again it is impossible to draw any conclusions from these test results.

When the test beams were oven-dried for 24 hours at 122°F at the completion of the testing program, five Barrier WD installations and one M-Coat F installation failed to regain resistance-to-ground values of 100 MΩ. This indicates that the moisture was trapped in the gage assembly or that deterioration within the gage assembly had begun.

All 17-4 PH stainless steel beams broke before load cycling tests were completed. The reason for these failures is uncertain, since the beams were hardened to condition H1025 with a minimum yield strength of 145,000 $lbf/in.^2$ and an impact strength of 40 ft-lb at -40°F (Armco Steel Corp. 1966). The fatigue strength of condition H1025 material is 88,000 $lbf/in.^2$ at 10 million cycles and 74,000 $lbf/in.^2$ at 100 million cycles; therefore, since the maximum theoretical stress induced in these beams was 75,000 $lbf/in.^2$, they should have endured almost 100 million cycles instead of the 150,000 to 400,000 cycles which they experienced.

Only two gage installations were found to have faulty lead wires at the conclusion of the tests. One of the wires was mechanically damaged, and indications were that failure occurred after all temperature and strain cycling was completed, leading to the conclusion that the insulation was probably damaged when removing the beam from the test apparatus. The other lead wire was faulty throughout its entire length, and since the gage assembly tested poorly during the first water immersion test, the conclusion is that a faulty length of lead wire was accidentally installed.

SUMMARY AND CONCLUSIONS

The Barrier D waterproofing is highly recommended for waterproofing strain gages subjected to low temperatures and water immersion, since all 12 installations survived all tests. Barrier E, with which 92% of the installations survived all tests, appears suitable for many field applications because it is so easy to apply. M-Coat F and M-Coat GL also had a survival rate of 92%, making both of them possibilities as low temperature waterproofing materials. Each of these systems possesses peculiar characteristics that should be considered before selection is made.

Barrier D is a hard epoxy coating which could reinforce thin specimens or low modulus specimens. The epoxy is viscous enough to apply on vertical surfaces. Although two thin coats are recommended for water immersion, one coat performed well in our tests. The system requires elevated temperature curing, which may limit its application.

Barrier E is simple to apply since it consists of only a rubber patch. Extra care must be taken to knead the soft rubber around the lead wires, which may be difficult in confined areas. The rubber patch remains pliable at low temperatures and will not cause significant localized reinforcement in the specimen.

M-Coat F provides more mechanical protection and a longer path length against water intrusion than Barrier E because of the aluminum foil. Although application is more complex than for either Barrier D or Barrier E, there may be certain applications where this extra effort is justified.

M-Coat GL is not to be used on open-faced gages or where it will come into contact with strong acids or solvents. It does not cause as much localized reinforcement as Barrier D, which makes it a more useful epoxy coating for thin or low modulus specimens.

Although our tests indicated one waterproofing system to be superior to all others, it should be emphasized that installation technique is very critical for all systems.

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APPENDIX A: CANTILEVER BEAM DESIGN

A free-body diagram of a typical beam is shown in Figure A1. The basic differential equation for a loaded beam is

$$\frac{d^2y}{dx^2} = -\frac{M}{EI} \tag{A1}$$

where M = bending moment
E = modulus of elasticity
I = moment of inertia.

For the loading shown in Figure A1

$$\frac{d^2y}{dx^2} = \frac{P(\ell-x)}{EI} \tag{A2}$$

and the boundary conditions are at $x = 0$, $dy/dx = 0$, $y = 0$, and at $x = \ell$, $y = y_{max}$. Integrating eq A2 and applying the first boundary condition, we obtain

$$\frac{dy}{dx} = \frac{1}{EI}\left(P\ell x - \frac{Px^2}{2}\right). \tag{A3}$$

Integrating again and applying the second boundary condition gives

$$y = \frac{P}{6EI}(3\ell x^2 - x^3). \tag{A4}$$

The stress due to bending in a beam is given by

$$s = \frac{Mc}{I} \tag{A5}$$

where s is the fiber stress and c the distance from neutral axis to point of interest.

Substituting the applicable bending moment for this cantilever beam we obtain

$$s = \frac{P(\ell-x)c}{I}. \tag{A6}$$

Combining eq A4 and A6 and using the third boundary condition for the beam, the following equation for stress results:

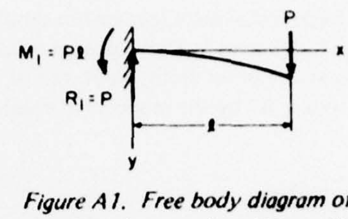

Figure A1. Free body diagram of cantilever beam, where P *is applied force,* R *reaction force, and* M *the reaction moment.*

$$s = \frac{3Ec(\ell-x)y_{max}}{\ell^3}. \tag{A7}$$

The maximum stress due to bending must be less than the yield strength of the beam material. This maximum stress occurs at $x = 0$ in eq A7, which gives

$$s_{yp} > \frac{3Ec\,y_{max}}{\ell^2} \tag{A8}$$

where s_{yp} is the yield strength of beam material. Solving eq A8 for length gives:

$$\ell > \sqrt{\frac{3Ec\,y_{max}}{s_{yp}}} \tag{A9}$$

For minimum yield strengths of 35,000 lbf/in.^{2} for mild steel, 35,000 lbf/in.^{2} for aluminum, and 145,000 lbf/in.^{2} for stainless steel, minimum respective lengths of 10.98 in., 6.34 in., and 5.36 in. were calculated from eq A9.

Since it was desirable to test as many beams as possible at one time, it was decided that 12 beams be tested, which would allow the test apparatus to be of a reasonable size for handling. Beam lengths chosen were 11.25 in. for mild steel, 8.75 in. for aluminum, and 7.50 in. for 17-4 PH stainless steel. Substituting these values for ℓ in eq A7 and evaluating the stress at $x=0$, we obtain the following maximum bending stresses: 33,333 lbf/in.^{2}, 18,367 lbf/in.^{2}, and 74,000 lbf/in.^{2} in the mild steel, aluminum, and stainless steel beams, respectively.

From eq A4 and the third boundary condition for the beam, we obtain the following expression for the load required to deflect the beam:

$$P = \frac{3EIy_{max}}{\ell^3} \qquad \text{(A10)}$$

When deflected 0.375 in., the forces required to deflect the beams are approximately 31 lbf for the mild steel, 22 lbf for the aluminum, and 103 lbf for the stainless steel. Total force required to simultaneously deflect four beams of each material is 624 lbf.

The strains at any point on the beam can be calculated by dividing A7 by the modulus of elasticity E:

$$\epsilon = \frac{3c(\ell - x)y_{max}}{\ell^3} \qquad \text{(A11)}$$

where ϵ = strain.

APPENDIX B: SPECIMEN PREPARATION

Twenty-four cantilever beam specimens — eight each of mild steel, aluminum, and stainless steel — were prepared. Four strain gages were applied to each, which required careful cleaning and degreasing of each of these locations. Twenty-four gage sites, on two beams of each of the three materials, were prepared at one time, since one adhesive would be used on these 24 gages.

The areas where the gages were to be located were initially degreased, then sandblasted to remove rust, oxides and scale, and subsequently smoothed using a small hand grinder. The areas were then sanded by hand using progressively finer sand paper, finally ending with 300-grit paper. At this stage the gage area must be free from pits or scratches, which may cause erroneous strain indications.

Chlorothene NU degreaser, a chlorinated hydrocarbon, was used to clean the entire beam. The beam was then placed on a clean glass surface and the gage sites and immediate surrounding areas were more thoroughly degreased. After both sides of each beam were degreased, the gage sites were etched using 300-grit emery paper wetted with M-Prep Conditioner A, which is a weak phosphoric acid compound. Gage alignment marks were then laid out using a degreased ruler and a ball point pen.

The alignment marks were made with only enough pressure to leave visible marks after the ink was washed off. Cotton swabs soaked in the acid were then used to repeatedly scrub the gage areas. The surface was considered sufficiently clean when a clean cotton tip did not discolor during scrubbing. Sufficient acid was used to maintain a wet metal surface during the scrubbing process. When the surface was judged to be sufficiently clean, a cotton swab soaked in the acid was passed over the cleaned area in one direction. This was repeated 4-5 times using a clean swab after each pass and always wiping in the same direction. Then a clean gauze pad was used to dry the area by making a single slow stroke through the cleaned area. This stroke began inside the cleaned area to prevent dragging contaminants into the cleaned area. Then another clean gauze pad was used and, beginning in the cleaned area again, a single stroke was made in the same direction. This conditioning process was repeated for both gage sites on one side of each beam. The beams were then turned over, being careful not to contaminate the cleaned areas, and the same procedure followed on the other side.

To bring the surface condition back to an alkalinity of between 7.0 and 7.5 pH for optimum strain gage adhesion, a neutralizer was required. Like the acid, neutralizer was applied with a cotton swab making 4-5 passes always in the same direction and always starting within the cleaned area. The surface was dried as before, using two clean gauze pads and wiping in two single strokes in the same direction. The surface was then ready for gage installation.

Each individual step was completed on both sides of the beams before proceeding to the next step. Otherwise, for example, if one side of the beam had been neutralized before the opposite side was conditioned with the acid solution, some of the acid may have accidentally been in contact with the neutralized surfaces, resulting in a poor adhesive bond between the gage and the specimen. Therefore, the beam was placed on a clean tissue paper during the gage preparation procedure; this tissue paper was changed after each individual step to avoid recontamination.

Gage installation immediately followed specimen preparation (i.e. the gage was mounted on the beam immediately after the neutralizing step); otherwise oxidation would have occurred on the prepared surface. Care was taken not to touch the cleaned area because natural skin oils would also contaminate the area.

APPENDIX C: GAGE INSTALLATION

Gages were bonded with two general types of adhesive — room temperature curing and elevated temperature curing. The only major difference in mounting procedure between the two types was that the elevated temperature cure required use of Teflon tape, while ordinary cellophane tape could be used to position the gages that were bonded with room temperature curing adhesive.

Gages were removed from the packages using a clean degreased pair of tweezers and placed, bonding side up, on a chemically clean glass sheet. The bonding surface of each gage was cleaned using M-Prep neutralizer. After the neutralizer had dried, the gage was turned over using clean tweezers. Pieces of tape long enough to extend beyond the edges of the gages and to permit folds at one end were applied to the gages. The tape-gage assemblies were then lifted very carefully off the glass surface and lowered over the gage alignment marks on the specimens. The tape over the properly aligned gages was smoothed to eliminate any air bubbles. After all four gages were aligned on each specimen, the tapes and gages were carefully peeled back from one end taking care to leave one end of the tape adhered to the specimen to aid in gage realignment. A uniformly thin coating of adhesive was then applied to each gage bonding surface and to the specimen, with the exception that EPY 150 and EPY 350 were applied to the gage bonding surface only.

The tape was then rolled back to its original position with the gage still accurately aligned. A piece of clean gauze was wiped firmly over the gage assembly, which picked up any excess adhesive squeezed from the edges of the tape and left a thin uniform layer of adhesive between the gage and the specimen. A thin sheet of Teflon was placed over the gage area to prevent the adhesion of the rubber pad, which was next installed to distribute clamping pressure evenly over the gage. Finally, an aluminum pad was placed over the rubber pad and the entire assembly taped down prior to clamping. The assembly was clamped to provide recommended clamping pressures for the particular installation. Spring clamps were used in this application because of their convenience. The adhesive was then cured according to the manufacturers' recommendations, which are summarized in Table CI. A typical completed gage installation on one side of a beam is shown in Figure C1.

Table CI. Curing schedule.

Adhesive	Clamping pressure ($lbf/in.^2$)	Cure temperature (°F)	Cure time (hr)
EPY 150	5-15	+70-+150	1-72*
EPY 350	5-15	350	2
PLD 700	35-45	500	2½
M-Bond 610	30-40	340	1½

* Depending upon temperature.

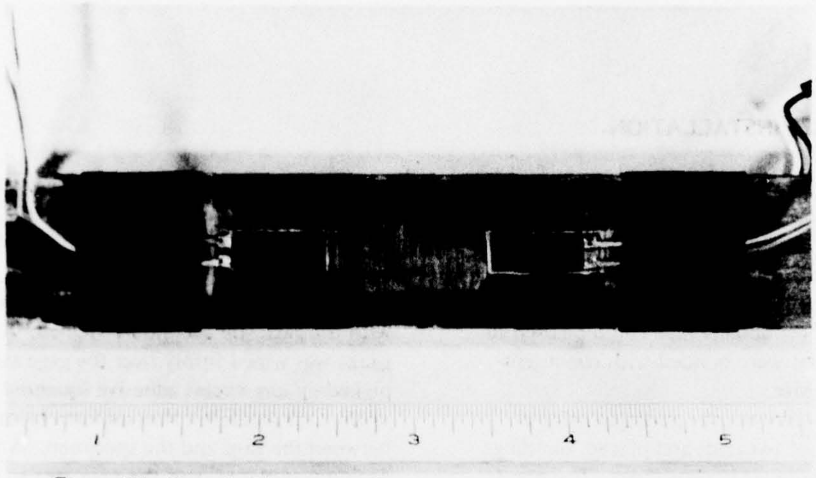

Figure C1. Completed gage installation before waterproofing application.